

# Evolution of ferromagnetic order in URhGe alloyed with Ru, Co and Si

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## Abstract

We have investigated the evolution of ferromagnetic order in the correlated metal URhGe (Curie temperature  $T_C = 9.5$  K) by chemical substitution of Ru, Co and Si. Polycrystalline samples  $\text{URh}_{1-x}\text{Ru}_x\text{Ge}$  ( $x \leq 0.6$ ),  $\text{URh}_{1-x}\text{Co}_x\text{Ge}$  ( $x \leq 0.9$ ) and  $\text{URhGe}_{1-x}\text{Si}_x$  ( $x \leq 0.2$ ) have been prepared and the magnetic properties have been investigated by magnetization and transport experiments. In the case of Ru doping,  $T_C$  initially increases, but then decreases linearly as a function of  $x$  and is completely suppressed for  $x_{\text{cr}} \approx 0.38$ . The Curie temperature in the  $\text{URh}_{1-x}\text{Co}_x\text{Ge}$  series has a broad maximum  $T_C = 20$  K near  $x = 0.6$  and then drops to 8 K for  $x = 0.9$ . In the case of Si doping  $T_C$  stays roughly constant. We conclude that the alloy systems  $\text{URh}_{1-x}\text{Ru}_x\text{Ge}$  and  $\text{URh}_{1-x}\text{Co}_x\text{Ge}$  are interesting candidates to study the ferromagnetic instability.

*Key words:* ferromagnetism, URhGe, chemical substitution, quantum phase transition

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## 1 Introduction

Recently, URhGe has attracted significant attention because ferromagnetism (Curie temperature  $T_C = 9.5$  K) and unconventional superconductivity ( $T_s = 0.25$  K) coexist at ambient pressure [1]. The superconducting state is believed to have its origin in the proximity to a ferromagnetic instability. Near the quantum critical point (QCP), which can be reached by tuning  $T_C$  to 0 K, enhanced ferromagnetic spin fluctuations mediate Cooper pairing (of the spin-triplet type [2]). The important role of critical magnetic fluctuations in URhGe is furthermore indicated by field-induced superconductivity for a magnetic field  $B$  directed along the orthorhombic  $b$ -axis [3]. It has been suggested that the high-field superconducting phase is due to magnetic fluctuations associated with the spin reorientation process which takes place at  $B \approx 12$  T [3]. Clearly, it is of considerable interest to further investigate the magnetic properties of URhGe, especially with respect to the proximity to a magnetic instability.

The crystallographic, magnetic, transport and thermal properties of URhGe have been investigated in much detail on polycrystalline as well as on single-crystalline samples [4,5,6,7,8,9,10,11,12]. URhGe crystallizes in the TiNiSi structure (space group  $Pnma$ ) [5]. Itinerant ferromagnetic order is found below  $T_C = 9.5$  K [4] and the ordered moment of about  $0.4\mu_B$ /U-atom points along the orthorhombic  $c$ -axis [1,11]. The linear electronic coefficient in the specific heat  $\gamma = 160$  mJ/molK<sup>2</sup> is enhanced, which indicates that URhGe is a correlated metal [7].

Here we report the evolution of ferromagnetic order in URhGe by doping with Ru or Co on the Rh site and Si on the Ge site. Our choice for the elements Ru and Co is motivated by the fact that URuGe and UCoGe are isostructural to URhGe and have a paramagnetic ground state [4,7,13]. This indicates doping with Ru or Co could possibly lead to a reduction of  $T_C$  and the approach to the magnetic instability. A large difference between both dopants is that Co is an isoelectronic substitution, while Ru is not. Notice that all other neighbouring isostructural UTGe compounds (here T is a transition metal) have a magnetic ground state: UIrGe, UNiGe and UPtGe are antiferromagnets, while UPdGe is a ferromagnet [4,14]. The compound URhSi is also isostructural to URhGe and ferromagnetic with a Curie temperature of 9.5 K [4,7,9].

The magnetic properties were studied by magnetization measurements on polycrystalline samples URh<sub>1-x</sub>Ru<sub>x</sub>Ge with  $x \leq 0.6$ , URh<sub>1-x</sub>Co<sub>x</sub>Ge with  $x \leq 0.9$  and URhGe<sub>1-x</sub>Si<sub>x</sub> with  $x \leq 0.2$ . The URh<sub>1-x</sub>Ru<sub>x</sub>Ge alloys were also investigated by electrical resistivity experiments. In the case of Ru doping  $T_C$ , after an initial weak increase, decreases linearly and vanishes at a critical Ru concentration  $x_{cr} \approx 0.38$ . Co doping leads to an increase of  $T_C$  up to 20 K for  $x = 0.60$ , beyond which  $T_C$  drops to 8 K for  $x = 0.9$ . In the URhGe<sub>1-x</sub>Si<sub>x</sub>

system no significant change of  $T_C$  was observed up to  $x = 0.20$ . A preliminary account of the evolution of magnetism in the  $\text{URh}_{1-x}\text{Ru}_x\text{Ge}$  series has been reported in Ref. [15].

## 2 Sample preparation, X-ray diffraction and experimental techniques

Polycrystalline samples  $\text{URh}_{1-x}\text{Ru}_x\text{Ge}$  ( $x \leq 0.6$ ),  $\text{URh}_{1-x}\text{Co}_x\text{Ge}$  ( $x \leq 0.9$ ) and  $\text{URhGe}_{1-x}\text{Si}_x$  ( $x \leq 0.2$ ) were prepared by arc melting the constituents U, Rh, Ru, Co (all 3N purity) and Ge and Si (both 5N purity) under a high-purity argon atmosphere. Each sample was melted several times and turned over after each melt to improve the homogeneity. The as-cast buttons were wrapped in Ta foil and annealed in quartz tubes under high vacuum for ten days at 875 °C. Samples for magnetization and transport experiments were cut by spark-erosion. Electron probe micro analysis showed the single phase nature of the samples within the resolution of 2%. X-ray powder diffraction confirmed the orthorhombic  $\text{TiNiSi}$  structure (space group  $Pnma$ ) [11,16] for all samples.

The lattice parameters of the  $\text{URh}_{1-x}\text{Ru}_x\text{Ge}$  series have been determined by X-ray diffraction for samples with  $x \leq 0.60$ . The results are shown in figure 1 together with literature data for pure  $\text{URuGe}$  [7]. For  $\text{URhGe}$  we obtain  $a = 6.887$  Å,  $b = 4.334$  Å and  $c = 7.513$  Å in good agreement with literature values (the uncertainty in the determination of the lattice parameters is about 0.1 %). The variation of the lattice parameters upon doping is anisotropic. The  $a$  lattice parameter shows the largest variation, it reduces linearly with increasing  $x$ . The  $c$  parameter shows a small increases, while the  $b$  parameter remains almost constant. The unit cell volume  $\Omega = 224.2$  Å<sup>3</sup> for  $\text{URhGe}$  follows Vegard's law and decreases linearly at a rate of 0.067 Å<sup>3</sup> per at.% Ru. The extrapolated value of  $\Omega$  for  $\text{URuGe}$  amounts to 217.5 Å<sup>3</sup>, which is slightly smaller than the literature value 219.5 Å<sup>3</sup> [7]. This difference is mainly due to the smaller extrapolated value for the  $b$  lattice parameter compared to the literature value (see figure 1).

The measured variation of the lattice parameters in the  $\text{URh}_{1-x}\text{Co}_x\text{Ge}$  series is shown in figure 2. Here the  $b$  and  $c$  lattice parameter show a linear decrease, while the  $a$  parameter remains almost constant. The unit cell volume decreases linearly at a rate of 0.152 Å<sup>3</sup> per at.% Co. For  $\text{UCoGe}$  we obtain  $a = 6.845$  Å,  $b = 4.206$  Å and  $c = 7.222$  Å, with  $\Omega = 207.95$  Å<sup>3</sup>, in good agreement with the literature values [13].

The lattice parameters for the  $\text{URhGe}_{1-x}\text{Si}_x$  alloys ( $x = 0.10$  and  $x = 0.20$ ) have not been determined. However, given the literature values for  $\text{URhSi}$

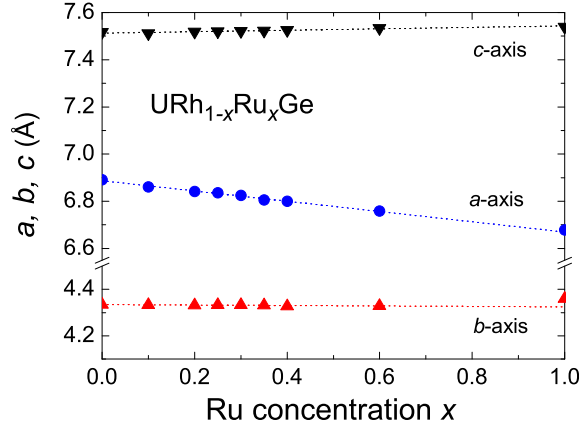


Fig. 1. Lattice parameters  $a$  (●),  $b$  (▲), and  $c$  (▼) of  $\text{URh}_{1-x}\text{Ru}_x\text{Ge}$  as a function of the Ru concentration  $x$  measured at room temperature. Data for URuGe are taken from Ref.[7]

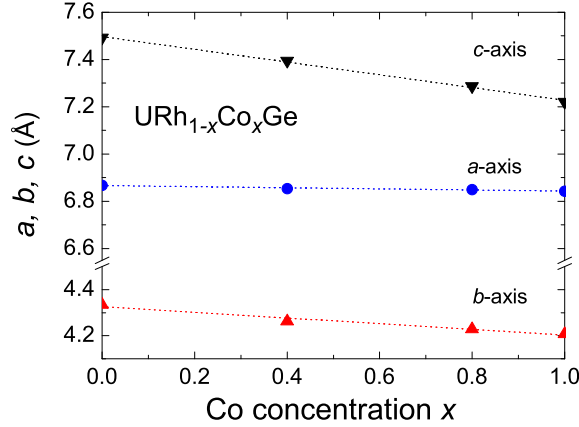


Fig. 2. Lattice parameters  $a$  (●),  $b$  (▲), and  $c$  (▼) of  $\text{URh}_{1-x}\text{Co}_x\text{Ge}$  as a function of the Co concentration  $x$  measured at room temperature.

( $a = 7.024$  Å,  $b = 4.121$  Å and  $c = 7.458$  Å) [17] and assuming Vegard's law, we conclude that the  $a$  parameter expands and the  $b$  and  $c$  parameters contract with increasing Si content. The unit cell volume decreases linearly at a rate of  $0.084$  Å<sup>3</sup> per at.% Si to  $\Omega = 215.9$  Å<sup>3</sup> for URhSi [17].

The dc magnetization  $M(T, B)$  was measured in a Quantum Design SQUID magnetometer. Temperature scans were made between 1.8 and 20 K in a field of 0.01 T and between 2 and 300 K in a field of 1 T. In both cases the data were taken after field cooling. Field scans of the magnetization were made in fields up to 5.5 T at several temperatures. The electrical resistivity,  $\rho(T)$ , was measured using a standard four probe low-frequency ac-technique in zero magnetic field from 2 to 300 K in a MagLab system (Oxford Instruments).

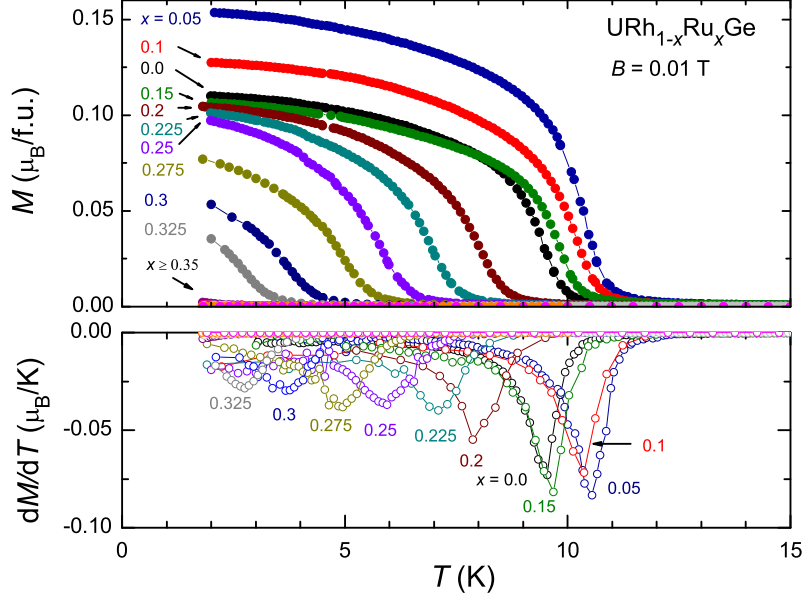


Fig. 3. Upper frame: Temperature variation of the dc magnetization measured in a field  $B = 0.01$  T of  $\text{URh}_{1-x}\text{Ru}_x\text{Ge}$  alloys with  $x \leq 0.6$  as indicated. Notice  $T_C$  first increases and has a maximum value for  $x = 0.05$ . For  $0.35 \leq x \leq 0.6$  magnetic order is not observed above  $T = 1.8$  K. Lower frame: Temperature derivative of the magnetization.

### 3 Experimental results

#### 3.1 $U(\text{Rh}, \text{Ru})\text{Ge}$ alloys

The temperature variation of the magnetization,  $M(T)$ , of the  $\text{URh}_{1-x}\text{Ru}_x\text{Ge}$  series measured in a field of 0.01 T is shown in figure 3. Also shown, in the lower part of the figure, is the derivative  $dM(T)/dT$ . The inflection point in  $M(T)$  or the temperature at which  $dM(T)/dT$  has a minimum defines the Curie temperature  $T_C$ . For pure  $\text{URhGe}$  we find  $T_C = 9.6$  K, in good agreement with previous values reported in the literature [1,4,7]. Upon replacing Rh by Ru the ferromagnetic transition first shifts upwards to 10.6 K for  $x = 0.05$ . For higher concentrations magnetic order is suppressed in a monotonic way. At  $x = 0.15$ ,  $T_C$  attains the same value as for pure  $\text{URhGe}$  and beyond  $x = 0.20$   $T_C$  decreases approximately linearly with  $x$  at a rate of 0.45 K/at.% Ru. For the samples with  $x = 0.35, 0.375, 0.40$ , and  $0.60$   $T_C$  no magnetic transition was observed in the measured temperature range ( $T > 1.8$  K).

For all samples in addition the field variation of the magnetization,  $M(B)$ , was measured up to 5.5 T at a number of fixed temperatures. By making Arrott plots, i.e. by plotting the data as  $M^2$  versus  $\mu_0 H/M$ , we identify  $T_C$  by the isotherm that intersects the origin. A typical Arrott plot is presented in figure 4

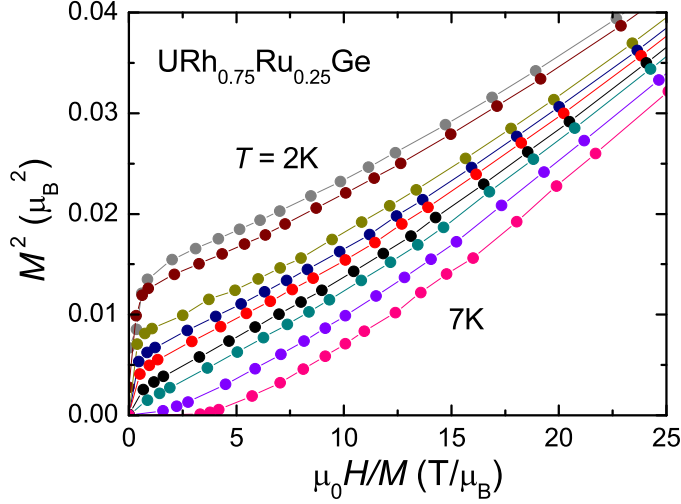


Fig. 4. Arrott plot of the magnetization of  $\text{URh}_{0.75}\text{Ru}_{0.25}\text{Ge}$ . The isotherms were measured (from top to down) at  $T = 2.0, 3.0, 4.5, 5.0, 5.3, 5.7, 6.0, 6.5$  and  $7.0$  K. The isotherm through the origin determines  $T_C = 6.0$  K.

for  $x = 0.25$ . Ideally the isotherms should be linear. For the  $\text{URh}_{1-x}\text{Ru}_x\text{Ge}$  alloys, the initial increase of  $M^2$  as a function of  $\mu_0 H/M$  is caused by demagnetization effects. The upward curvature at higher values of  $\mu_0 H/M$  is due to reorientation processes (from the easy axis to the applied magnetic field) [3] of the magnetic moments in our polycrystalline samples. The Curie temperatures deduced from the Arrott plots (neglecting the small error in the determination of  $T_C$  due to demagnetization effects) are in good agreement with those derived from the minimum in  $dM(T)/dT$ . For  $x = 0.25$  we find  $T_C = 6.0$  K. The Arrott plot of the compound with  $x = 0.35$  (not shown) suggests that ferromagnetism sets in near  $T_C \sim 1.3$  K. This value of  $T_C$  is estimated by extrapolating the intersection points of the isotherms with the  $\mu_0 H/M$  axis to the origin of the Arrott plot. For  $x = 0.375$   $T_C$  is close to zero, while for  $x = 0.40$  and  $0.60$  the Arrott plots clearly indicate a paramagnetic ground state.

In figure 5 we have plotted the reciprocal susceptibility,  $1/\chi$ , of a few selected  $\text{URh}_{1-x}\text{Ru}_x\text{Ge}$  alloys, measured in a field  $B = 1$  T in the temperature range 2-300 K. The strong magneto-crystalline anisotropy, observed on single-crystalline samples [11], hampers a proper analysis of the high-temperature local-moment susceptibility in our polycrystalline samples, using the modified Curie-Weiss law  $\chi(T) = C/(T - \theta) + \chi_0$  (here  $\chi_0$  represents a temperature independent contribution). However, the overall upward shift of the curves with increasing Ru contents indicates an increasing (antiferromagnetic) interaction strength  $\theta$ . The analysis is further complicated by the strong curvature of  $1/\chi$  versus  $T$  which signals crystalline electric field effects. Note that in pure  $\text{URhGe}$  the easy-axis ( $c$ -axis) susceptibility measured on a single crystal does follow a modified Curie Weiss behavior with  $\theta \approx T_C$ , as demonstrated in

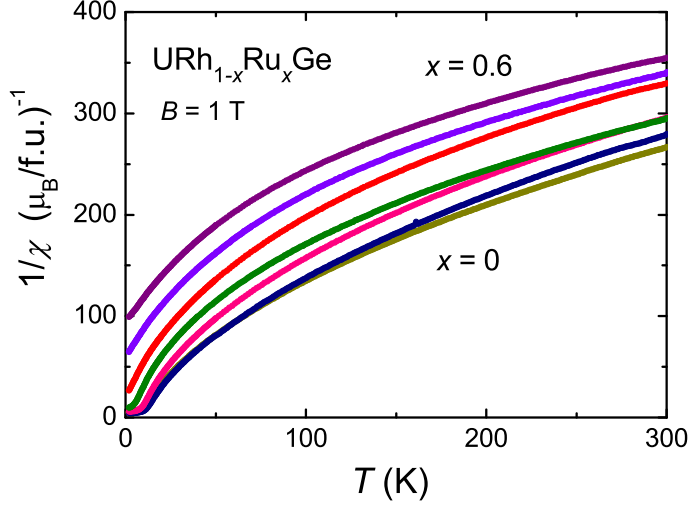


Fig. 5. Temperature variation of the inverse susceptibility  $1/\chi$  of  $\text{URh}_{1-x}\text{Ru}_x\text{Ge}$  alloys measured in a field of 1 T. Ru concentrations are (from bottom to top)  $x = 0, 0.1, 0.2, 0.3, 0.4, 0.5$  and  $0.6$ .

Ref. [1].

The electrical resistivity  $\rho(T)$  of the  $\text{URh}_{1-x}\text{Ru}_x\text{Ge}$  alloys is shown in figure 6. Note the vertical scale is in arbitrary units. For  $x \geq 0.60$  the overall temperature variation (see right panel in figure 6) is consistent with the formation of a Kondo-lattice, i.e. an increase of the resistivity upon lowering  $T$  below 300 K, a weak maximum in the temperature range 70 – 130 K and a steady drop signaling coherence at low temperatures. For all doped samples the absolute variation of the resistivity in the temperature interval 2 – 300 K amounts to 150-250  $\mu\Omega\text{cm}$ , which are usual values for uranium intermetallics [6,14]. The residual resistivity values  $\rho_0$  are large (200-300  $\mu\Omega\text{cm}$ ) and do not follow a systematic variation with Ru concentration. This we mainly attribute to the brittleness of the samples (cracks). Consequently, the residual resistance ratio's ( $\text{RRR} = R(300\text{K})/R(2\text{K})$ ) are small ( $\approx 2$ ). The left panel in figure 6 shows  $\rho(T)$  in the temperature interval 2-20 K. For  $x = 0$  the kink in  $\rho(T)$  signals the Curie temperature,  $T_C = 9.4$  K, in agreement with the magnetization data. Below  $T_C$  the resistivity is dominated by spin-wave scattering, while for  $T \geq T_C$  spin-disorder scattering is dominant. With increasing  $x$  the kink becomes less pronounced. However, for all  $x \leq 0.30$   $T_C$  can be identified by the maximum in  $d\rho/dT$  (arrows in figure 6). The Curie temperatures determined in this way are in good agreement with those obtained by the magnetization measurements.

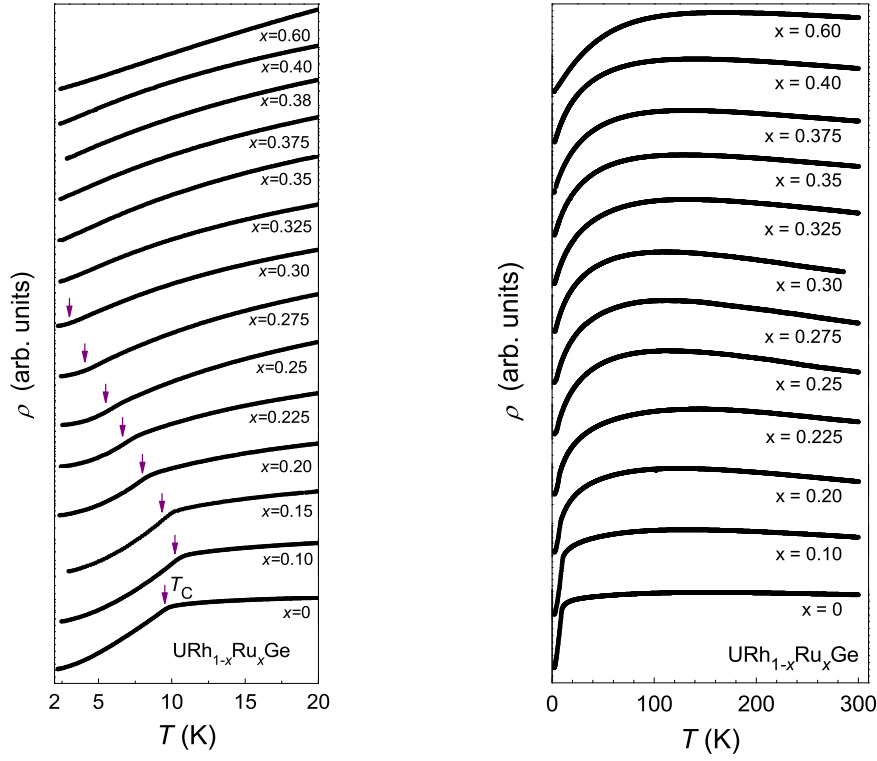


Fig. 6. Temperature dependence of the electrical resistivity  $\rho$  in arbitrary units of  $\text{URh}_{1-x}\text{Ru}_x\text{Ge}$  alloys for  $0 \leq x \leq 0.6$  as indicated. Left panel:  $2 \text{ K} \leq T \leq 20 \text{ K}$ . The Curie temperatures are indicated by arrows. Right panel:  $2 \text{ K} \leq T \leq 300 \text{ K}$ .

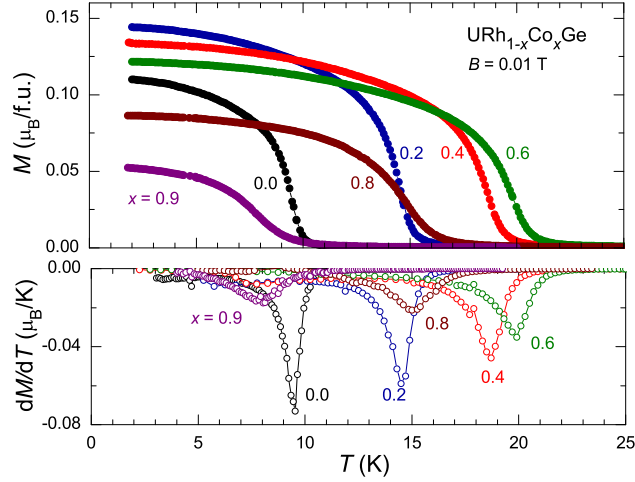


Fig. 7. Upper frame: Temperature variation of the dc magnetization measured in a field  $B = 0.01 \text{ T}$  of  $\text{URh}_{1-x}\text{Co}_x\text{Ge}$  alloys with  $x \leq 0.9$  as indicated. Notice  $T_C$  has a maximum value for  $x = 0.6$ . Lower frame: Temperature derivative of the magnetization.



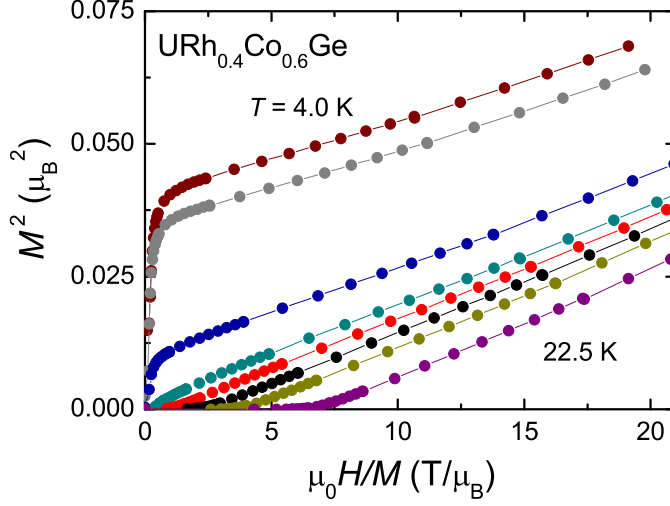


Fig. 8. Arrott plot of the magnetization of  $\text{URh}_{0.4}\text{Co}_{0.6}\text{Ge}$ . The isotherms were measured (from top to down) at  $T = 4.0, 10.0, 18.5, 20.0, 20.5, 21.0, 21.5$  and  $22.5$  K. The isotherm through the origin determines  $T_C = 20.0$  K.

### 3.2 $U(\text{Rh}, \text{Co})\text{Ge}$ alloys

The temperature variation of the magnetization,  $M(T)$ , and its derivative  $dM(T)/dT$ , for the  $\text{URh}_{1-x}\text{Co}_x\text{Ge}$  series measured in a field of 0.01 T is shown in figure 7. The effect of Co doping differs from that by Ru doping.  $T_C$  increases monotonically up to  $x = 0.6$ , where it reaches a value of 20 K, i.e. more than twice the value for  $x = 0$ . For higher values of  $x$ ,  $T_C$  decreases and drops to 8.0 K for  $x = 0.9$ . Since  $\text{UCoGe}$  has been reported to be paramagnetic (at least for  $T \geq 1.2$  K) [4,7], the data suggest that  $\text{UCoGe}$  is close to ferromagnetic order. The proximity to a ferromagnetic instability was previously proposed on the basis of high-field magnetization measurements (at  $T = 4.2$  K) in which a relatively large field-induced magnetic moment of  $0.58 \mu_B$  was observed in a field of 35 T [8]. The variation of  $T_C$  with Co concentration has also been tracked with help of Arrott plots. The Arrott plot for  $x = 0.6$ , where ferromagnetic order is most robust, is shown in figure 8. In figure 9 we show the reciprocal susceptibility measured in 1 T. The curves for various amounts of Co doping are very similar, which indicates that the Curie-Weiss constant  $\theta$  does not vary much. The data for  $x = 0.2$  and  $0.4$ , and  $x = 0.0$  and  $0.8$  largely overlap. This indicates the data do not represent a polycrystalline average, and our samples contain crystallites with preferred orientations.

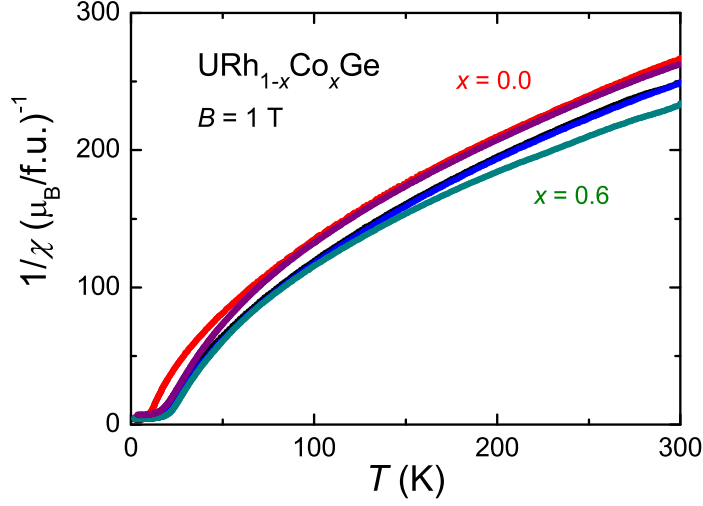


Fig. 9. Temperature variation of the inverse susceptibility  $1/\chi$  of  $\text{URh}_{1-x}\text{Co}_x\text{Ge}$  alloys for measured in a field of 1 T. The Co concentrations are  $x = 0.0, 0.2, 0.4, 0.6, 0.8$ . The data for  $x = 0.2$  and  $0.4$ , and  $x = 0.0$  and  $0.8$  largely overlap.

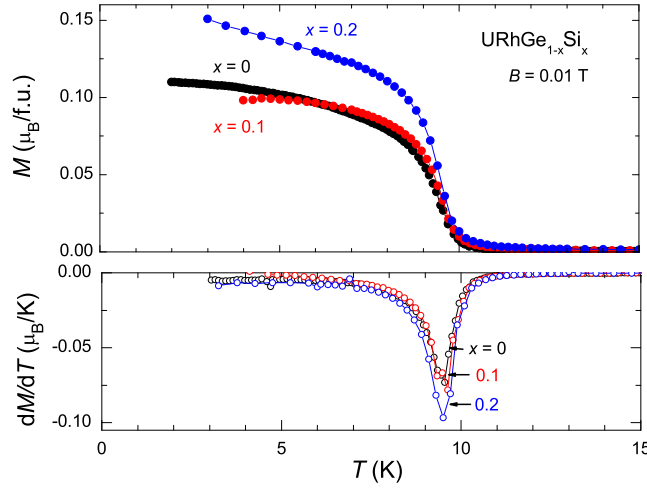


Fig. 10. Upper frame: Temperature variation of the dc magnetization measured in a field  $B = 0.01$  T of  $\text{URhGe}_{1-x}\text{Si}_x$  alloys with  $x = 0, 0.1$  and  $0.2$  as indicated. Notice  $T_C$  stays roughly constant. Lower frame: Temperature derivative of the magnetization.

### 3.3 $\text{URh}(\text{Ge}, \text{Si})$ alloys

In figure 10 the magnetization measured in 0.01 T as a function of temperature is shown for the  $\text{URhGe}_{1-x}\text{Si}_x$  series with  $x \leq 0.20$ . Ferromagnetic order is robust in the case of Si doping. The Curie temperatures deduced from  $(dM(T)/dT)_{\min}$  agree with those deduced from the Arrott plots, as expected.  $T_C$  does not change with the Si content up to  $x = 0.20$ . The reciprocal suscep-

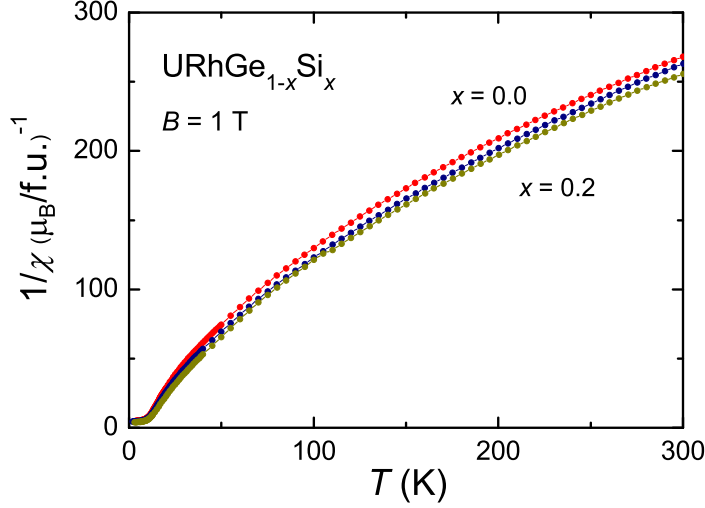


Fig. 11. Temperature variation of the inverse susceptibility  $1/\chi$  of  $\text{URhGe}_{1-x}\text{Si}_x$  alloys measured in a field of 1 T. Si concentrations are (from top to bottom)  $x = 0$ , 0.1 and 0.2.

tibility, plotted in figure 9, shows only a weak variation with the Si content.

#### 4 Discussion

The main results of our study of the evolution of ferromagnetic order in  $\text{URhGe}$  doped with Ru, Co and Si, namely the variation  $T_C(x)$ , is presented in figure 12. The  $T_C(x)$  curves for Ru and Co substitution follow a similar trend:  $T_C$  first increases, has a maximum near  $x = 0.05$  and  $x = 0.60$  for Ru and Co doping, respectively, and then vanishes near  $x = 0.38$  and  $x \sim 1.0$ , respectively. However, in a quantitative measure Ru is more than twice as effective as Co in suppressing  $T_C$ . Doping up to 20 at.% Si on the Ge site does not suppress ferromagnetic order and  $T_C$  remains 9.4 K. Since for the end compound  $\text{URhSi}$  the Curie temperature has the same value [4], the data suggest  $T_C \approx 9.4$  K in the entire  $\text{URh}(\text{Ge},\text{Si})$  series.

The evolution of magnetic order in correlated  $4f$ - and  $5f$ -electron metals is often discussed in terms of a simple Doniach picture [18], where the competition between the on-site Kondo interaction and inter-site RKKY (Ruderman-Kittel-Kasuya-Yosida) interaction determines the ground state. In the Doniach model the control parameter is the ratio of the exchange interaction  $J$  over the bandwidth  $W$ . Keeping  $W$  constant, a weak hybridization ( $J$  small) favours the RKKY interaction and a magnetic ground state, while a strong hybridization ( $J$  large) favours a non-magnetic Kondo-screened ground state. In the generic Doniach phase diagram the magnetic ordering temperature  $T_M$  goes through a maximum with increasing  $J$  and vanishes when the RKKY

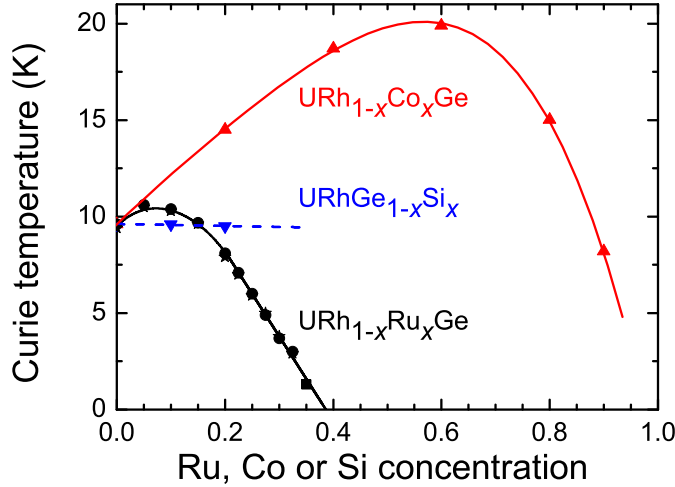


Fig. 12. Variation of the Curie temperature  $T_C$  of URhGe doped with Ru ( $\bullet$  from magnetization,  $\star$  from transport), Co ( $\blacktriangle$ ) and Si ( $\blacktriangledown$ ). The solid lines serve as a guide to the eye. The data point for URh<sub>0.65</sub>Ru<sub>0.35</sub>Si ( $\blacksquare$ ) is determined by extrapolation in the Arrott plot for  $x = 0.35$  (see text). The critical concentration for the suppression of ferromagnetic order is  $x_{\text{cr}} \approx 0.38$  for Ru doping and  $x_{\text{cr}} \approx 1.0$  for Co doping.

and Kondo energies become comparable. A typical example of a ferromagnetic material that follows the generic Doniach phase diagram is cubic CeAg ( $T_C = 5.6$  K) [19]. Here hydrostatic pressure is used to control  $J$  via the unit cell volume, such that  $T_C(P)$  goes through a broad maximum near 0.7 GPa. For the orthorhombic UTX alloys (X is Ge or Si)  $J$  is not controlled by the unit cell volume and the effects of hybridization are difficult to control because of the strongly anisotropic magnetic and electronic properties [14]. For instance, resistivity measurements under hydrostatic pressure on pure URhGe show that  $T_C$  increases linearly up to very high pressures ( $T_C$  reaches  $\approx 17$  K at 13 GPa) [20], in disaccord with the Doniach phase diagram.

Nevertheless, it is interesting to compare the volume effects due to alloying and hydrostatic pressure. Assuming an isothermal compressibility  $\kappa = -V^{-1}(dV/dp)$  of  $\approx 0.8$  Mbar<sup>-1</sup> [12], substitution of 1 at.% Ru, Co or Si leads to a chemical pressure of 0.37 kbar, 0.91 kbar or 0.46 kbar, respectively. Using  $dT_C/dp = 0.065$  K/kbar as derived from the resistivity measurements under pressure [20] we calculate an increase of  $T_C$  per at.% Ru, Co or Si of 0.024, 0.059 and 0.030 K. In the case of Ru and Co doping these calculated values are about a factor 5 too small when compared to the measured initial increase in  $T_C$ , while in the case of Si doping  $T_C$  does not increase at all. Clearly, chemical and mechanical pressure give different results. Magnetization measurements under pressure on URhGe doped with 0.325 at.% Ru ( $T_C = 2.8$  K at ambient pressure) did not show a noticeable change of  $T_C$  for a pressure of 4.3 kbar [21]. This indicates an additional complication, namely  $dT_C/dp$  varies with doping concentration.

A striking difference between Co and Si doping on the one hand and Ru doping on the other hand is that the first two substitutions are isoelectronic, while the latter depletes the  $d$ -band. In a simple model, extracting electrons from the  $d$ -band results in an additional strengthening of the  $f$ - $d$  hybridization, which in turn leads to a larger exchange parameter  $J$ , favoring the Kondo interaction. Specific-heat measurements on  $\text{URh}_{1-x}\text{Ru}_x\text{Ge}$  support this idea [21,22]. The linear coefficient of the electronic specific heat  $\gamma$  increases as a function of  $x$  and reaches a maximum value near  $x_{cr} = 0.38$ , i.e. the critical concentration for the suppression of ferromagnetic order. For isoelectronic Co and Si doping, the (in)variance of  $T_C(x)$  is attributed predominantly to anisotropic hybridization phenomena related to the anisotropic variation of the unit cell parameters. It would be interesting to investigate whether more sophisticated models, like the one proposed by Sheng and Cooper [23], could explain the observed behaviour of the magnetic ordering temperature. By incorporating the change in the  $f$ -density spectral distribution under pressure in LMTO band-structure calculations, these authors could explain the observed maximum in the magnetic ordering temperature for compounds like UTe.

The  $\text{URh}_{1-x}\text{Ru}_x\text{Ge}$  series deserves ample attention because it might present one of the rare opportunities to investigate a ferromagnetic quantum critical point in  $f$  electron systems at ambient pressure. Evidence for a ferromagnetic quantum critical point is provided by measurements of the low-temperature electronic specific heat  $c(T)$  [21,22]. At the critical Ru concentration  $x_{cr} \approx 0.38$  a pronounced non-Fermi liquid term  $c \propto T \ln T$  is observed over a wide temperature interval 0.5-9 K. Such a behaviour has been proposed within the itinerant electron model for a ferromagnetic quantum critical point [24,25,26].

## 5 Conclusions

We have investigated the evolution of ferromagnetic order in the correlated metal  $\text{URhGe}$  by substitution of Ru, Co and Si. Magnetization measurements, and in case of Ru also resistivity measurements, have been performed and the variation of the Curie temperature has been extracted from the data. In the case of Ru and Co doping,  $T_C$  goes through a maximum near  $x = 0.05$  for Ru doping and  $x = 0.60$  for Co doping.  $T_C$  vanishes near  $x = 0.38$  for Ru doping and  $x \approx 1.0$  for Co doping. Si doping does not affect  $T_C$  (at least up to  $x = 0.20$ ). For Ru, as well as for Co doping  $T_C(x)$  follows the generic Doniach phase diagram, but anisotropic hybridization effects hamper a quantitative analysis. Depletion of the  $d$ -band enhances the suppression of magnetic ordering in the case of Ru doping. We conclude that the alloy systems  $\text{URh}_{1-x}\text{Ru}_x\text{Ge}$  with  $x_{cr} \approx 0.38$  and  $\text{URh}_{1-x}\text{Co}_x\text{Ge}$  with  $x_{cr} \approx 1.0$  are interesting candidates to investigate the ferromagnetic instability.

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## References

- [1] D. Aoki, A. Huxley, E. Ressouche, D. Braithwaite, J. Flouquet, J.P. Brison, E. Lhotel and C. Paulsen, *Nature (London)* **413** (2001) 613.
- [2] F. Hardy and A.D. Huxley, *Phys. Rev. Lett.* **94** (2005) 247006.
- [3] F. Lévy, I. Sheikin, B. Grenier and A.D. Huxley, *Science* **309** (2005) 1343.
- [4] R. Troć and V.H. Tran, *J. Magn. Magn. Mat.* **73** (1988) 389.
- [5] B. Chevalier, B. Lloret, P. Gravereau, B. Buffat and J. Etourneau, *J. Magn. Magn. Mat.* **75** (1988) 13.
- [6] V.H. Tran, R. Troć and D. Badurski, *J. Magn. Magn. Mat.* **87** (1990) 291.
- [7] K.H.J. Buschow, E. Brück, R.G. van Wierst, F.R. de Boer, L. Havela, V. Sechovský, P. Nozar, E. Sugiura, M. Ono, M. Date and A. Yamagishi, *J. Appl. Phys.* **67** (1990) 5215.
- [8] F.R. de Boer, E. Brück, V. Sechovský, L. Havela and K.H.J. Buschow, *Physica B* **163** (1990) 175.
- [9] V.H. Tran, R. Troć and G. André, *J. Magn. Magn. Mat.* **186** (1998) 81.
- [10] I.H. Hagmusa, K. Prokeš, Y. Echizen, T. Takabatake, T. Fujita, J.C.P. Klaasse, E. Brück, V. Sechovský and F.R. de Boer, *Physica B* **281-282** (2000) 223.
- [11] K. Prokeš, T. Tahara, Y. Echizen, T. Takabatake, T. Fujita, I.H. Hagmusa, J.C.P. Klaasse, E. Brück, F.R. de Boer, M. Diviš and V. Sechovský, *Physica B* **311** (2002) 220.
- [12] S. Sakarya, N.H. van Dijk, A. de Visser and E. Brück, *Phys. Rev. B* **67** (2003) 144407.
- [13] F. Canepa, P. Manfrinetti, M. Pani and A. Palenzona, *J. Alloys Comp.* **234** (1996) 225.
- [14] V. Sechovský and L. Havela, *Handbook of Magnetic Materials* Vol. 11, ed. K.H.J. Buschow (North Holland, Amsterdam, 1998) p. 1.
- [15] S. Sakarya, N.H. van Dijk, N.T. Huy and A. de Visser, *Physica B* **378-380** (2006) 970.

- [16] B. Lloret, *Ph.D. Thesis* (University of Bordeaux I, 1988).
- [17] K. Prokeš, E. Brück, K.H.J. Buschow, F.R. de Boer, V. Sechovský, P. Svoboda, X. Hu, H. Maletta and T.J. Gortenmulder, *J. Appl. Phys.* **79** (1996) 5221.
- [18] S. Doniach, *Physica B* **91** (1977) 231.
- [19] A. Eiling A and J.S. Schilling, *Phys. Rev. Lett.* **46** (1981) 364.
- [20] F. Hardy, A. Huxley, J. Flouquet, B. Salce, G. Knebel, D. Braithwaite, D. Aoki, M. Uhlarz and C. Pfleiderer, *Physica B* **359-361** (2005) 1111.
- [21] S. Sakarya, *Ph.D. Thesis* (University Delft, 2007).
- [22] N.T. Huy *et al.*, to be published.
- [23] Q.G. Sheng and B.R. Cooper, *J. Appl. Phys.* **75** (1985) 7035.
- [24] G.R. Stewart, *Rev. Mod. Phys.* **73** (2001) 797.
- [25] H. von Löhneysen, A. Rosch, M. Vojta and P. Wölfle, e-print cond-mat/0606317.
- [26] A.J. Millis, *Phys. Rev. B* **48** (1993) 7183.